Next Generation Space Telescope

Group 1 Trades

Science Drivers

Prepared for the NGST Study Manager

by

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1.0 Scope:

As part of the *NGST* Study Plan, we summarize the *NGST* Science Drivers for the Group 1 Trades. Commensurate with Group 1 philosophy, we describe these "drivers" in general terms and indicate further studies that will be undertaken to refine the quantitative goals for the *NGST* mission. Nevertheless, we anticipate that the quantitative results will not be significantly different from the prioritized list in Section 4. They can be listed as:

• The *NGST* has been recommended by the *HST & Beyond* Committee to be a large aperture, passively cooled telescope of greater than 4m effective aperture to follow *HST* & *SIRTF*. Only telescopes of this size will be capable of detecting the faint structures which have evolved into galaxies such as our Milky Way.

• The *NGST* must be long-lived, to permit extensive IR research by the astronomical community, responding to the discoveries made by NGST, in addition to completing a defined set of major investigations such as the study of the earliest galaxies and stars and the geometry of the universe.

• The *NGST* will exploit the low zodiacal background and diffraction-limited wide field optics to study the early universe by observing the redshifted light from newly forming stars as they are redshifted into the near-IR (0.5-5 microns).

• The *NGST* will exploit the low internal background of the observatory to provide observational capabilities in the thermal-IR (5-30 microns) comparable to those available at optical wavelengths.

This document also reflects recommendations and corrections made during the 4 April, Group 1 Trade discussions.

2.0 Background:

The idea for a large, passively cooled observatory to follow *HST* and *SIRTF* predates the deliberations of the AURA *HST & Beyond* Committee (1993-95). In 1989, a passively cooled observatory was the centerpiece of the Next Generation Space Telescope Workshop; and Tim Hawarden presented the *POIROT* (Passively-cooled, Orbiting, Infra-Red, Observatory Telescope) concept to the ESA Astrophysics Working Group. The potential of such an observatory, which could gain the advantages of low temperatures without the constraints and weight of cryogenics, was well appreciated by the UV-Optical Astronomy from Space subpanel of the 1990 NAS decadal survey; and its recommendation for significant technology development in this area was carried forward in the summary report. Both NASA and ESA held workshops to discuss the relevant technologies in 1991 (Astrotech 21 and the European workshop on Next Generation Infrared Space Observatories). More recently, the *Edison* mission (a 2-m class passively cooled observatory) has been proposed for an ESA M3 mission; and *High-Z* (a 4-m thin mirror version of Edison) was submitted to NASA as an advanced mission concept. The latter mission was influenced by the *New Technology Orbiting Telescope* which was a dual-use of a 4-m facility for Star Wars studies and astronomy.

Following the successful *HST* First Servicing Mission, the AURA *HST & Beyond* Committee could view the scientific landscape at the nominal end of the *HST* mission in the light of new and exciting *HST* images of the distant universe as well as plans for future space and ground capabilities. The installation of the Near Infrared Camera and Multi-Object Spectrograph (NICMOS) and the Space Telescope Imaging Spectrograph (STIS) in 1997 would both extend the sensitivity of the *HST* into the near-IR and improve its UV spectrographic efficiency. The Advanced Camera for Surveys (ACS) has been chosen for development and installation in 1999 and promises to further increase the sensitivity and imaging performance of the *HST* in UV-Optical-Near-IR imaging. Meanwhile, the cryogenic *ISO* and *SIRTF* missions will improve the sensitivity of IRAS and groundbased observatories in the mid-far infrared by several orders of magnitude. On the ground, the 10m aperture Keck I & II telescopes are paving the way for almost a dozen large aperture, lightweight telescopes. These ground-based facilities will use modern cooling technologies to reduce internal "seeing" and adaptive optics to obtain diffraction-limited imaging performance in the 2.2 micron atmospheric window. At shorter wavelengths, laser-guide star technology may provide diffraction-limited imaging at optical wavelengths but only for narrow fields of view (a few arcseconds).

The *HST & Beyond* Committee recommended that the greatest gains from space would be made by
1) extending the *HST* mission, even at greatly reduced support;
2) developing a large aperture, passively cooled observatory for the near and thermal IR; and
3) developing interferometric techniques to discover planets around nearby stars.

In addition, the Committee realized that major technology and management improvements would be required to accomplish these goals within foreseeable funding levels. In considering the *NGST*-type mission, the Committee clearly considers it to be open to a broad community of astronomers and scientific studies (i.e. not PI mode). This has significant implications for the design of the mission.

3.0 Science Goals:

The *HST&B* Committee considered a large, passively cooled telescope essential for studies of the early universe at redshifts greater than z=2-3. For Omega = 1, the z=4 epoch is 90% back in time or only 1 - 1.5 billion years old. The light from stars at that epoch will be redshifted to 5 times their nominal wavelength. Visible light will appear at approximately 2 microns. Earlier epochs will be shifted to even longer wavelengths. In the near-IR, groundbased observations are severely affected by atmospheric absorption and emission and the thermal radiation of the telescope optics. With angular resolution comparable or superior to that obtained under optimum conditions with adaptive optics, a large passively cooled space telescope will enjoy 1000 times less background and will be capable of extending the exquisite sensitivity of *HST* to wavelengths of 3-5 microns, depending on the effective aperture. The *HST & B* Report shows the theoretical performance of a passively cooled 4m compared to the SOFIA and Gemini observatories. The 4-m *NGST* is >100 times more sensitive than either of these observatories and can observe in wavelength regions which are completely obscured by atmospheric absorption. An 8-m *NGST* would be 4 times more sensitive (16 times faster) than a 4-m.

Although far superior to groundbased and airplane based observatories, a passively cooled telescope in an orbit 1 AU from the sun will be limited by the thermal emission by the dust in our solar system which increases rapidly longward of 4-5 microns and effectively creates a natural break in deep cosmological studies. This break is shifted to longer wavelengths and the background lowered overall by more than an order of magnitude at greater distance from the Sun. That is the reason for considering a 1-3AU elliptical orbit (circularizing at 3 AU is probably out of the question). Initial studies show that a >4-m *NGST* will be capable of observing a bright, newly formed galaxy at very high redshift (z > 10) independent of the cosmology. As a benchmark, if the *NGST* can observe to a limiting flux magnitude of AB(1-4 microns)=31 =1.4 nJy in 10,000s, it can detect a supernova at a redshift of z>12 and a newly formed globular cluster to a redshift of z=5-9 (Omega=0.1, 1 respectively). We chose these sensitivities as minimum science drivers, with sensitivities of AB=32.5 or 0.4nJy as goals to ensure spectroscopic followup of these sources.

3.1 Supernovae & Cosmology: Supernovae can be used as standard candles to directly study the geometry of the universe (qo, Lambda, Omega, and Ho) and also as indicators of star formation rates and the creation of heavy elements (carbon, nitrogen, oxygen, and the silicon-iron groups). Moreover, association of supernovae with known redshifts with the faintest resolved sources may be the best way to establish their nature and distances. Present day surveys by Perlmutter and others are likely to provide initial values for these parameters and for star formation rates at redshifts up approximately z=1.5 At higher redshifts, the light from supernovae at maximum light will be shifted into the near-IR. We anticipate that both the cosmological issues and rates of star formation at earlier epochs will not be settled by 2005. *NGST* will be uniquely capable of both discovery of distant supernovae and their spectroscopic followup. Since the number of galaxies observed by *NGST* will exceed several thousand per image and we expect to see approximately 0.0001-0.0003 supernova per galaxy at any given time, it is clear that 100s of cosmologically distant supernovae can be studied in the course of a 1/4-1/2 year survey of 1000 fields. The nature and depth of that survey will depend on the fundamental geometry of the universe. The greatest sensitivity is required for an open universe, Omega < 0.1, but the volume probed in a given image will be maximized. For a flat universe, Omega=1, the available volume probed in an image is reduced but the supernovae will appear brighter so that the survey would consist of many images with less sensitivity. The time to obtain a statistically significant number of galaxies is inversely proportional to the near-IR imager Field Of View (FOV) in square arcminutes. Thus one of the science drivers for *NGST* is a sufficiently large FOV to execute the supernova survey in approximately 1/2 year. To capture supernovae on the rise to maximum light and permit follow-up spectroscopy will require the ability to follow survey fields for the typical rise time (two weeks in the rest frame) and initial decline (another 15 days). These time frames are extended by a factor of (1+z) for redshifted objects. For supernovae near z=2 region, that corresponds to a period of 75 days. For higher redshifts, a different strategy may be required, perhaps viewing the field to establish a baseline and then returning a year later to discover supernovae near their peak and initial decline. For redshifts of z=4, the decline corresponds to a period of 75 days. For redshifts as high as z=8-9, the survey field may be revisited over several years to establish the decline rate. The need to revisit a low-zodiacal-light, survey field for a period 2-2.5 months is critical to the success of a supernova survey.

3.2 Early Galaxies: We know from the Lyman-alpha forest absorption line data that the sky is completely covered by faint galaxies and gas clouds as we look beyond redshifts of z=1. However, most of these objects have very low surface brightnesses, even in their rest frame. Nevertheless, confusion is an important factor in the study of the early universe. The Hubble Deep Field images indicate the incredible complexity and richness that can be expected for deep *NGST* images. *SIRTF*, with superb sensitivity but resolution of only 1.5 arcsec, will only be able to study the most luminous, largest galaxies at redshifts of z=2-3. At lower flux levels and greater redshifts, *SIRTF* will become confusion limited. The HDF image indicates that *NGST* will require the resolution of *HST* (<0.1 arcsec) to ensure that it does not become confusion limited at comparable or greater sensitivities. Although more detailed studies are required to define the best methods for studying the early formation of galaxies, we know that the task will be difficult. Like the supernova survey, the depth and angular coverage of the deep galaxy survey will depend on the curvature of the Universe. Moreover, the number of high redshift galaxies will be a small fraction of the total number of galaxies visible. That is due to the lower effective volume at high redshifts and the many, low luminosity foreground galaxies which will be detected by *NGST*. However, it is precisely the sensitivity and large wavelength coverage of *NGST* which will permit the elimination of foreground objects based upon their colors. Detecting a faint source at visible wavelengths basically establishes the object as foreground with the redshifted Lyman Alpha < 0.5 microns ,or z < 3. Since groundbased telescopes will not be capable of 0.1 arcsec imaging at visible wavelengths over wide fields even with laser guide stars due to the small isoplanatic patch, NGST should include the capability for wide field, visible imaging (although not necessarily diffraction limited imaging).

Follow-up spectroscopy of faint galaxies will be the most difficult requirement for *NGST*. Ideally, it should be possible to obtain low resolution (R=100) near-IR spectra of distant supernovae and galaxies with only a modest increase in observing time. The *HST & B* report recommends a resolution of R=1000 for a variety of follow-up observations. In practice, the fluxes from the faintest point sources will be too low to be detected after they has been dispersed into 1000 wavelength regions-- unless there are strong emission lines. For intermediate redshift candidates (z=1-3), we expect that large ground-based telescopes will be used to obtain spectra at visible wavelengths, detecting the Lyman alpha break and CIV emission features. Newly formed, bright Lstar galaxies with redshifts of z=8-10 may be identified with *NGST* through spectroscopy-- if such galaxies exist. Here, the strongest science drivers argue for low-noise detectors (<0.1 e/s thermal currents,) and the largest possible collecting areas. For detector-limited spectroscopy, these two performance characteristics are equally important. The spectroscopic "speed" of the *NGST* will be proportional to the square of the total area of the main mirror divided by the detector thermal currents.

3.3 Mid-IR Studies: The *HST & B* Committee recognized that a large passively cooled space observatory could provide imaging and spectroscopic capabilities in the mid or thermal IR (5-30 microns) which surpassed facilities such as *Gemini* and *SOFIA* by more than three orders of magnitude. The large 8-m groundbased telescopes approach the sensitivity of an *NGST* only for very bright objects -- objects which are much brighter than the zodiacal background. (In the near-IR, the *HST & B* report's conservative assumption of 10 e/s thermal current compared to the 0.1-0.2 e/s achieved with InSb devices does not do the *NGST* performance justice -- today's detectors are already an order of magnitude better.) The *SIRTF* science mission emphasizes this spectral region and will establish the baseline science that *NGST* will pursue at over 100 times the speed. Thus, the potential scientific return from a long-lived, passively cooled observatory working in the mid-IR is extraordinary and beyond the reach of our current observational experience. The improvement is comparable to the difference between groundbased visible astronomy in 1900 and 1970 -- or 1970 and 1996. In this regime, we argue that the sensitivity of the mid-IR portion of the mission may be somewhat compromised to gain breadth (capabilities and wavelength coverage). However, the guidance of the *HST & Beyond* Committee is that the cost of adding the mid-IR wavelength region should not significantly increase the cost of the mission. Since the overall imaging and mission performance of the *NGST* will be driven by the short wavelength goals, we anticipate that supporting the general scientific Drivers for the mid/thermal IR will have the following implications: the need for a separate, low wavelength detector, fore-optics, and cooling; and the lowest temperature for the telescope and instrument module which can be achieved without active cooling. We elaborate upon these capabilities and impacts below.

3.3.1 Mid-IR Detectors & Cooling Requirements: The most likely detectors for the 1-5 micron band will be capable of operating at a temperature compatible with passive cooling (30-50K). This is highly desirable for reliability and long-life. However, low-background detectors for the thermal IR will need to be cooled by stored cryogenics or closed-cycle coolers to temperatures well below those levels ($T < 10K$). Thus, to extend *NGST* into the mid/thermal IR will require special detectors and some form of active cooling. Both the cost of the different detector(s) and the cost and weight of cooling systems must be modest. Thus, we argue that the long wavelength portion of the instrument bay be a multipurpose imager/spectrometer with capabilities commensurate with using a single mid-IR detector assembly.

3.3.2 Optical Temperatures and the Long-wavelength cutoff: The temperature of the *NGST* optics and instrument assembly will have its greatest effects in the mid/thermal IR bandpass. The thermal flux from the several optical surfaces will begin to exceed the zodiacal light background at 20-30 microns for optics temperatures of 45-30K respectively and will climb exponentially at longer wavelengths. For a simple camera mode, with only one set of actively -- or conductively -- cooled filters, this will limit the ultimate bandpass to these values. We anticipate that for spectroscopic modes the entire mid-IR portion of the instrument bay will need to be cooled to temperatures $T < 20K$. Otherwise the wavelength cutoff will need to be substantially shorter in order that thermal radiation scattered into the beam doesn't exceed the detector thermal currents. Whether this is difficult or easy will guide the design. Depending on the degree of thermal loading, this may preclude long focal lengths and high resolution within the mid-IR channel. Thus, while we will maintain a goal of 30 microns for the long wavelength cutoff, spectroscopy at such long wavelengths may not be feasible within a modest cooling budget. The desire to use a common detector assembly for imaging and spectroscopy in the mid/thermal IR may imply that the cutoff wavelength must be the shorter of the two modes in order to not compromise the other. Thus, if the detector must be designed for a cutoff at 20 microns in order not to double the effective thermal background in spectroscopy, it would not be capable of longer wavelength imaging observations. Any compromise between the imaging and spectroscopy mode performance will be modest given the rapid increase in thermal radiation at longer wavelengths. It is important, however, to investigate the use of longpass blocking filters, which could be cooled and inserted for low-noise spectroscopy in the mid-IR.

3.4 A General User Facility

The unprecedented capabilities of *NGST* in the near and mid-IR will impact a broad range of astronomical fields. Thus, we anticipate that after (or during) the initial early galaxy and supernovae surveys, observing time will be allocated to General Observers (GOs) based upon competitive peer review. The wavelength range covered (0.5-30 microns) is an order of magnitude broader than that accessible by *HST*. The demand and quality of the science programs will be correspondingly greater. A minimum mission length may be defined as the time required for the core survey programs (about 1.5 years) and approximately double that period for a GO program. Thus a 5 year mission length is a major science driver. To provide an opportunity for an improved, perhaps more focused survey as well as a second generation GO program to follow the analysis and publication of results from the initial GO program, we anticipate a mission lifetime goal of 10 years. To encourage the rapid publication of results, a maximum proprietary period of 1 year should be given to both the deep survey and GO programs. The supernova survey may require an additional year for the proprietary period to permit the analysis of two/three epoch imaging.

4.0 Science Drivers:

In the previous section, we have collected the following science drivers based upon the *HST & Beyond* Committee report. We also provide first order estimates for the performance characteristics these imply. We also indicate drivers which result from the need to have a broad base of users. We suggest that Priority 1 capabilities are central to the successful design and success of the *NGST* mission. Performance trades can be made within the Priority 1 drivers but must reach satisfactory performance for each element. Priority 2 capabilities are very important to the success of the mission. Generally, they permit more extensive scientific research programs and are important "insurance" against nasty surprises by Nature or unforeseen changes in the direction of astronomical studies. Priority 3 capabilities are examples of important capabilities in which *NGST* will be very competitive with ground-based and other space-based facilities. These capabilities enhance the *NGST* mission and should be designed for unless they entail significant resources or impact higher priority items. Priority 4 capabilities may extend current ground and space capabilities but are not recommended because of their high cost or anticipated impact on the observatory.

Priority 1 Drivers
(Core of *HST*&B recommendations)

Description	Impact
Zodiacal-light limited imaging performance (1-5 microns) to reach the point source and surface brightness sensitivities to study early galaxies.	Requires T_optics < 70 K, HEO or L2 orbit, capable of pointing 60-70 degrees from sunline to minimize zodiacal light.
Sensitivity to observe newly formed globular clusters at redshifts of z=5-9 (1.4 nJy in 10^4 s, 10 sigma)	Requires minimum of 12m^2 aperture
A 1.5 year survey program and 3.5 year GO program in the near & mid-IR.	A 5 year minimum lifetime. Requires adequate expendables
Obtain statistically significant number of early galaxy and supernovae detections in the 1.5 year survey.	Large FOV for near-IR surveys. Requires large arrays (>3x3 arcmin, 4096x4096)
Ability to obtain follow-up spectroscopy (redshifts and energy distributions) of 10 sigma survey sources, (1-5 microns, R=100-1000)	Large collecting area & low noise 2D detectors, efficient fiber, microlens, or slicer optics
Imaging performance at 1-2 microns equivalent to HST to avoid reaching the confusion limit in deep surveys.	4-8m maximum baseline, 60-100 mas FWHM

Priority 2
(Very Important *NGST* Capabilities)

Description	Impact
Background limited-Multipurpose mid/Thermal IR capabilities from 5-microns to 20 microns to follow-up SIRTF discoveries in mid/thermal IR.	Low noise detectors (5-30 microns) with active cooling, emphasizes thermal design and low instrument bay temperatures (40K).
Wide Field-Imaging capabilities in the visible to permit identification of faint, foreground galaxies/fragments.	Requires CCDs or similar detectors. Gold coatings OK.
All sky-pointing, at least once per year, to support first rank GO program.	Requires large sun-shield, and pointing perpendicular to sun-line.
Provide for focused studies after the initial deep surveys and follow-up after publications of three cycles of GO programs.	10 year mission goal.
Ability to obtain R=1000 spectroscopy of z=5 galaxies and 5 sigma survey sources.	Emphasizes larger collecting areas, 8m goal.
Ability to revisit selected supernova fields over 2.5 months to observe the rise to maximum light of supernovae (z=2) and execute follow-up spectroscopy.	Impacts sun-shield design and requires significant sky coverage (>20%).

Priority 3
(Competitive *NGST* Capabilities)

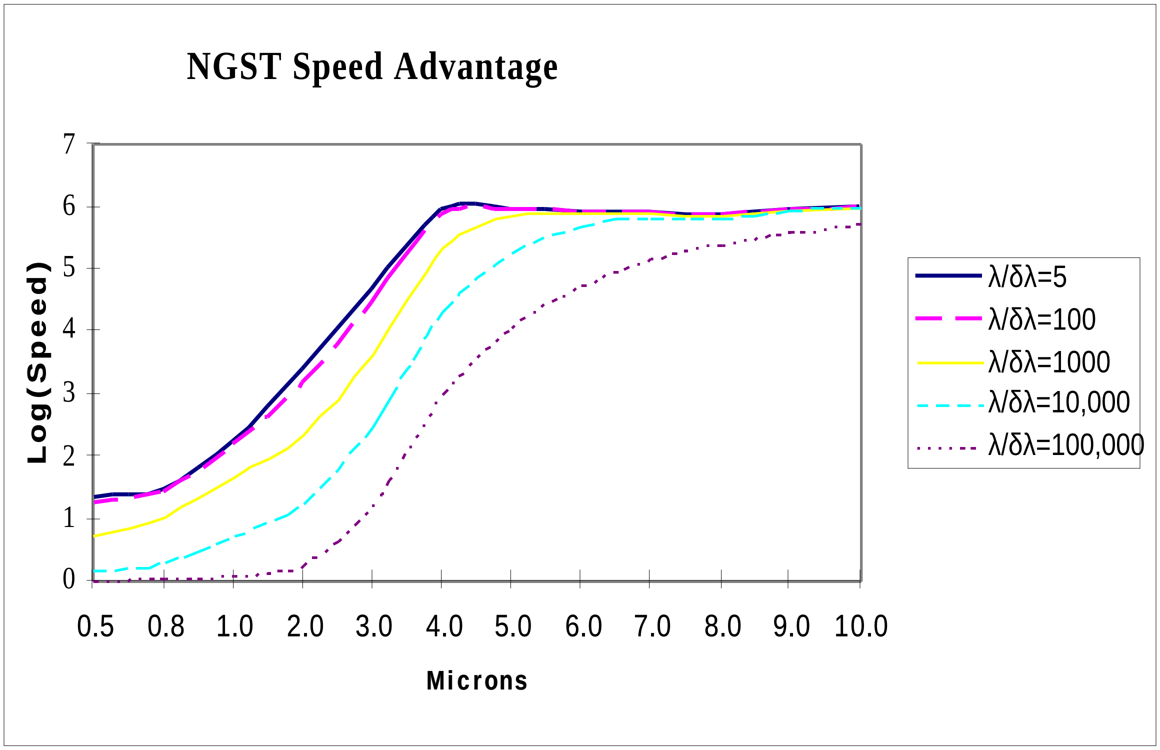
Description	Impact
Moderate Resolution Near-IR Spectroscopy to study the earliest AGN at redshifts of z=7-10 and velocity dispersions in galaxies at redshifts of z=4-5. (2.5-5 microns, R=5-10,000, no overlap with ground capabilities in these near-thermal wavelengths)	May require additional spectrographic channel and detector.
Mid-IR Coronagraphy: Unique capability for use in direct detection of large planets and thermal emission due to dust at 2-3 AU in possible exosolar solar systems.	May require additional imaging channel and detector. Most interesting for 8-m NGST.

Priority 4 Capabilities
(Not Recommended)

Description	Rationale
Extension to UV (<0.3 microns; extends HST coverage of this region)	Contamination issues, additional channels and detectors, would require development of low-temp UV detectors if solar blind.
High Resolution near-IR spectroscopy(1-5 microns, R>>10,000)	Groundbased facilities will develop these for working between the atmospheric lines.
Extension to Far-IR (>50 microns)	Competes with FIRST & MM Arrays, poor use of limited FOV, needs additional active cooling.

5.0 Speed Advantages of NGST -- Another Method Of Determining Priorities

As a sanity check on the priorities listed in the previous section, we may calculate the "speed advantage" of an 8-m, passively cooled telescope relative to the best ground facilities. Defined as the ratio of times required for the ground-based telescope and the space-based telescope to obtain a background-limited flux level, the speed advantage for a major space mission must be approximately 100 or more to justify a major mission capability. In the figure below, we indicate the speed advantage of a 8-m *NGST* compared to a 8-m, *Gemini*-class telescope for imaging (a spectral resolution of $\lambda/\delta\lambda$ = R= 5) and four increasing resolutions for spectroscopy, R = 100, 1000,10,000, & 100,000. We have assumed moderate advances in detector technology and reasonable values for the atmospheric background and telescope emissivity, but we conservatively neglect the atmospheric absorption bands.



The figure shows that the *NGST* is > 100 times faster than a 8-m ground-based telescope for imaging and low resolution spectroscopy at approximately 1.0 microns. However, the high resolution spectroscopy only reaches the factor of 100 advantage at approximately 3.5 microns. This is because the high resolution disperses the background light so that it becomes comparable to the detector dark current. For wavelengths beyond 5 microns, however, the gains are remarkable for all resolutions. These results are entirely consistent with the priorities in the previous tables. In particular, there is only a weak argument for moderate resolution spectroscopy, R=10,000, below 2.5 microns on *NGST*. This is a regime which will be exploited by high resolution spectrographs on *SOFIA* and ground-based telescopes. Note that we have not included the effects of atmospheric absorption bands and have assumed that the atmosphere is purely emissive with negligible absorption. This is a reasonable simplifying assumption below 3 microns but understates the advantage of the NGST facility longward of 3 microns.

The influence of aperture size is significant both in terms of absolute sensitivity and scientific strategy. In the next figure, we show a comparable performance chart for the 0.85m *SIRTF* aperture diffraction limited at 5 microns and the same, improved detectors. What is striking about the figure is that the larger groundbased apertures overwhelm the cryogenic advantage of a *SIRTF*-sized aperture shortward of 3 microns. Again, the chart does not illustrate the effects of atmospheric absorption, which is significant longward of 2.2 microns and particularly longward of 10 microns. The aperture advantage enjoyed by ground-based telescopes drives the *SIRTF* cryogenic mission goals to longer wavelengths, lambda > 4 microns.